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Quantum-well plasma instability in the resonant tunneling regime

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Abstract. The resonant tunneling is accompanied by the accumulation of the 2D electrons in the well between the barriers of the double-barrier heterostructures. It leads to the $I-V$ curve of Z-type in the high-quality structures. We have shown that it also leads to the instability of the 2D plasmons in the quantum well. The build up of the instability can give rise to the lateral static domains in the tunnel current, that in its turn results in the kinks in the region of the central arm of Z of the $I-V$ curve.

As a rule the double-barrier resonant tunneling structures (DBRTS) have the $I-V$ curves of N-type [1]. However in the high quality structures the accumulation of the 2D electrons in the quantum well (QW) of the DBRTS is to result in the transformation of the $I-V$ curve of N-type to that of Z-type [2]-[6]. If one uses the ordinary experimental technique (say, the load line is close the vertical one), it is seen as hysteresis or bistability in the $I-V$ curve. A new experimental technique has been proposed recently, where a negative load resistance is realized [7]. The technique allows one to measure the $I-V$ curves of Z-type. An additional peak in the region of the central arm of Z was observed with the help of the technique [8]. The interpretation of the experimental results [7], [8] depends on the solution of the stability problem of the homogeneous (along the QW) distribution of the currents and charges in the DBRTS with respect to the inhomogeneous perturbation in the Z-type region of the $I-V$ curve. The first part of the paper is devoted to the solution of the problem. The problem is formulated in the terms of the 2D plasmons – low-frequency charge oscillations in the QW. The second part of the paper is devoted to the the static nonlinear nonhomogeneous distribution of the tunnel current and charge density in the QW.

1 The spectrum of 2D plasmons in the QW

We consider the DBRTS in the sequential tunneling model. The set of equations describing the time and spatial $(x,\ y)$ distribution of the currents and potentials in the QW consists of the material Eq. (1), continuity Eq. (2), the Eq. (3) that follows from the Poisson equation in the local capacitance approximation, the equations for the emitter-well (J_{ew}) (4) and well-collector (J_{wc}) (5) tunnel currents, respectively:

$$\frac{\partial \mathbf{J}}{\partial t} + \nu \mathbf{J} = \frac{\sigma \nu}{e} \nabla E_{\text{fw}}, \tag{1}$$

$$-e\frac{\partial}{\partial t} N_{\text{2D}} + \nabla \mathbf{J} = J_{\text{ew}} - J_{\text{wc}}, \tag{2}$$

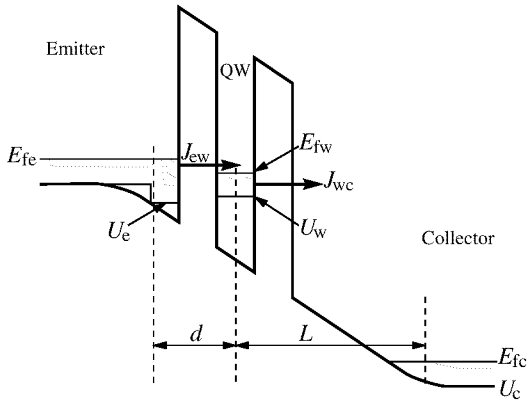

Fig. 1. The energy diagram of the DBRTS in the regime of the resonant tunneling.

$$V - V_0 = \frac{e^2}{C} N_{2D} - \left(E^0_{fe} - E^0_{fc}\right) \frac{d}{L+d}, \tag{3}$$

$$J_{ew} = -\left[E_{fe} - E_{fw} - (E_{fe} - U_w)\,\theta(U_w - E_{fe})\right] \rho_{2D} \frac{e}{\tau_e} \tilde{\theta}(V), \tag{4}$$

$$J_{wc} = -N_{2D} \frac{e}{\tau_c}, \tag{5}$$

see the notations in Fig. 1. $\mathbf{J}(x, y)$ is the density of the 2D current in the QW; $V = U_w - U_e$. For simplicity we supposed that the bottom of the 2D subband in the QW is higher than the Fermi energy in the emitter, when the energy shift due to the external bias (V_{ext}) is equal to zero, $V = V_0$ in the case. ρ_{2D} is the 2D density of states in the QW, $N_{2D} = [E_{fw} - U_w]\rho_{2D}$ is the local 2D concentration of the electrons in the QW, τ_e and τ_c are the life times of electrons in the QW due to the tunneling to the emitter and collector, respectively. $C = \epsilon(L + d)/4\pi Ld$, $\nu = 1/\tau$ is the reciprocal momentum relaxation time in the QW, $\sigma = N_{2D}e^2/m^*\nu$ is the static 2D conductance of the QW. The form-factor $\tilde{\theta}(V)$ describes the broadening of the resonant levels. If the broadening is neglected, $\tilde{\theta}(V) = \theta(V)$, where $\theta(V)$ is the step function. One gets the known Z-type $I-V$ curve from the set of Eqs. (1)–(5) if all the variables are supposed to be static and homogeneous (we use the superscript "0" for the solution).

Linearizing the Eqs. (1)–(5) in the vicinity of the homogeneous static solution, one gets [ ] the set of equations describing the screened 2D plasmon in the QW. The dispersion Eq. of the 2D plasmons is:

$$(\omega + \imath\nu)(\omega + \imath\nu_T) = \frac{\sigma^0\nu}{C}\left(1 + \frac{C}{e^2\rho_{2D}}\right) q^2, \tag{6}$$

$$\nu_T = \frac{1}{\tau_c} + \frac{\tilde{\theta}(V^0)}{\tau_e} + \frac{e^2\rho_{2D}}{C}\left[\frac{\tilde{\theta}(V^0)}{\tau_e} - \frac{\left[E_{fe} - U_e - V^0\right]}{1 + \tilde{\theta}(V^0)\tau_c/\tau_e}\frac{\tilde{\theta}'(V^0)}{\tau_e}\right], \tag{7}$$

here q is the 2D wavevector of the plasmons. The plasmons are unstable in time when $Im(\omega) > 0$. The analysis of the Eqs. (6) and (7) (see [ ]) shows that 2D plasmons are unstable in the central arm of Z of the $I-V$ curve: (i) in the case of $-\nu < \nu_T < 0$ provided

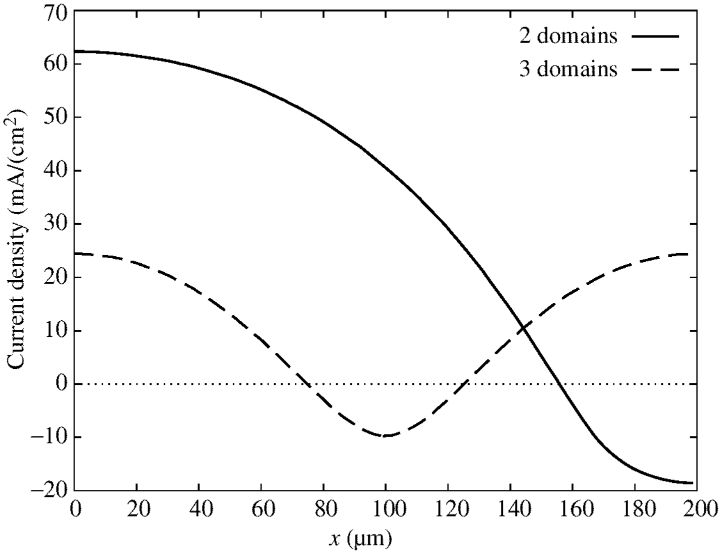

Fig. 2. The deviation of the tunnel current from the homogeneous solution in the case of 2 domains (full curve) and 3 domains (dashed curve).

$q < q_0$ (i.e. the width of DBRTS is sufficiently large: $W > \pi/q_0$); (ii) in the case of $-\nu_T > \nu$ and arbitrary values of W and q; here

$$q_0 = \sqrt{-\frac{\nu_T C}{\sigma^0}\left(1 + \frac{C}{e^2\rho_{2D}}\right)^{-1}}. \tag{8}$$

The instability does not depend on the external circuit. For the parameters of DBRTS taken from Refs. [7, 8] length $\pi/q_0 \approx 150\,\mu$m.

2 Inhomogeneous nonlinear solution

If $-\nu < \nu_T < 0$ the 2D plasmons build up without oscillations in time in the central arm of Z of the $I-V$ curve. The increase in amplitude should be stopped by the nonlinear effects. The nonlinear static solutions follow from the set of Eqs. (1)–(5). They describe the domain-like distribution of the tunnel current and the 2D charge in the QW. For the illustration of the phenomenon we present here the calculation result of the inhomogeneous tunnel current distribution (see Fig. 2) and the $I-V$ curve (see Fig. 3). The parameters of the DBRTS where taken from the papers [7, 8]. Due to the appearance of the domain structure in the tunnel current, the kinks appear in the central arm of Z of the $I-V$ curve (see Fig. 3) that qualitatively corresponds to the experimentally observed [8] features of the $I-V$ curve of Z-type.

3 Conclusions

We have shown that in the high quality DBRTS with the $I-V$ curve of Z-type, the 2D screened plasmons are unstable in the central arm of the Z in the following cases: (i) in the structures of any width (W) if $\nu_T < -\nu$; (ii) in sufficiently wide structures ($W > \pi/q_0$)

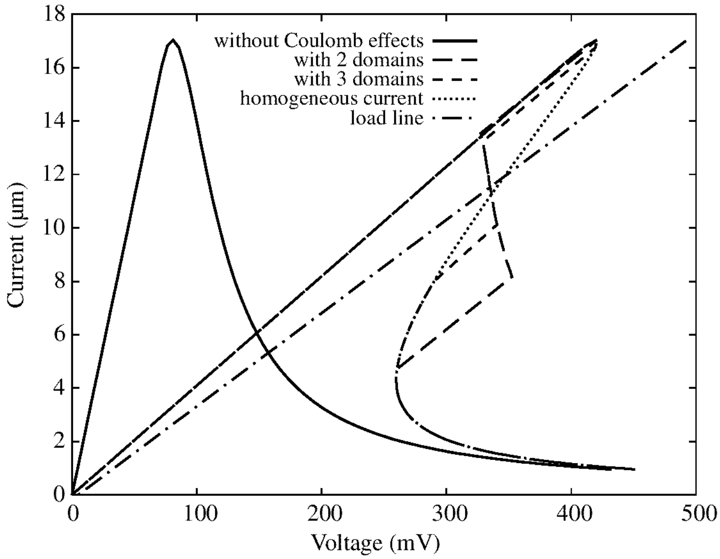

Fig. 3. The $I-V$ curves of the DBRTS.

if $-\nu < \nu_T < 0$. The instability does not depend on the external circuit and the load resistance may be positive as well as negative. The build up of the instability can give rise to the static domains in the tunnel current, that in its turn results in the kinks in the Z-region of the $I-V$ curve. The result is in a qualitative agreement with the experiment [8].

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References

[1] H. Mizuta and T. Tanoue, *The Physics and Applications of Resonant Tunneling Diodes* Cambridge University Press, 1995.
[2] F. W. Sheard and G. A. Toombs, *Appl. Phys. Lett.* **52**, 1228 (1988).
[3] V. J. Goldman, D. C. Tsui and J. E. Cunningham, *Phys. Rev. Lett.* **58**, 1256 (1987).
[4] A. Zaslavsky, V. J. Goldman, D. C. Tsui and J. E. Cunningham, *Appl. Phys. Lett.* **53**, 1408 (1988).
[5] R. K. Mains, J. P. Sun and G. I. Haddad, *Appl. Phys. Lett.* **55**, 371 (1988).
[6] H. L. Berkowitz and R. A. Lux, *J. Vac. Sci. Technol.* **B5**, 967 (1987).
[7] A. D. Martin, M. L. F. Lerch, P. E. Simmonds and L. Eaves, *Appl. Phys. Lett.* **64**, 1248 (1994).
[8] C. Zhang, M. L. F. Lerch, A. D. Martin, P. E. Simmonds and L. Eaves, *Phys. Rev. Lett.* **72**, 3397 (1994).
[9] M. N. Feiginov and V. A. Volkov, *JETP Lett.* **68** (8), 633 (1998).